

Diatoms as Indicators of Freshwater Flow Variation in Central California

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Abstract

Diatoms from tidal marsh sediments collected from Rush Ranch, north of Suisun Bay, are used to reconstruct the history of salinity variability in the northern part of San Francisco Bay over the past 3,000 years. Evidence suggests that the primary factor controlling the distribution of diatoms is the salinity gradient within the estuary. The composition of modern diatom assemblages in freshwater (<2‰), brackish (2‰ to 30‰), and salt water (>30‰) marshes were used to calibrate the late Holocene assemblages. Variations in both individual taxa and ecological assemblages were then used in the analysis of salinity variations. Dominant taxa in each ecological assemblage vary downcore, indicating that variation in salinity is only one parameter in a complex set of factors that control the temporal and spatial distribution of diatoms in San Francisco Bay marshes.

At the Rush Ranch site there appears to be evidence of broad-scale salinity cycles. Prior to European contact about 150 years ago, there are two intervals dominated by freshwater taxa (2,500 cal yr B.P. to 1,750 cal yr B.P. and 750 cal yr B.P. to about A.D. 1850) and two intervals dominated by brackish water and marine taxa (3,000 cal yr B.P. to 2,500 cal yr B.P. and 1,750 cal yr B.P. to 750 cal yr B.P.) The upper cycle appears to be broadly related to the Medieval Warm Interval (upper brackish interval) and the Little Ice Age (upper freshwater interval). Minor fluctuations during the last 2,700 years occur in a pattern similar to the lake level record for Mono and Pyramid lakes, which lie east of the crest of the Sierra Nevada. An increase in the abundance of fresh water diatoms at Rush Ranch occurs at about the same time as high stands, implying contemporaneous increases in precipitation on both sides of the Sierra Nevada.

Introduction

The brackish marshes in the northern part of San Francisco Bay occur at the interface between freshwater flow from the rivers of interior California and the salt water entering through the Golden Gate. About 40% of the land area of California drains through the estuary (Conomos 1979). Prior to European occupation, brackish marshes were extensive in Suisun Bay, located between the Sacramento-San Joaquin Delta and San Pablo Bay (Figure 1). Brackish marshes can be identified by a diversity of macrophytes (Atwater and others 1977). Diatom diversity is also higher in brackish marshes than in either the normal marine environment of San Francisco Bay or the fresh water of the Sacramento-San Joaquin Delta (Starratt and Wan 1998).

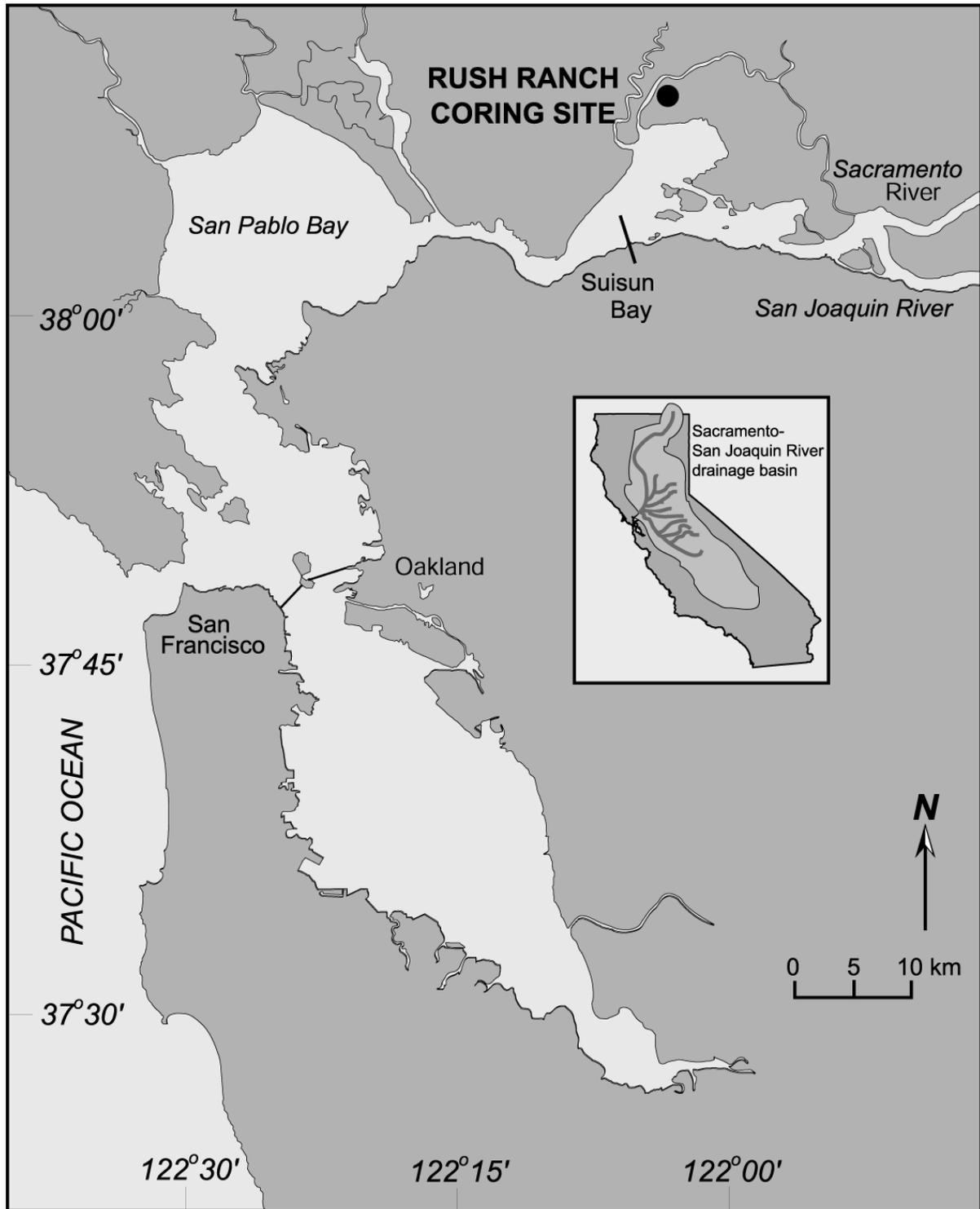


Figure 1 Map of San Francisco Bay showing the location of the Rush Ranch site and the drainage basin of the Sacramento and San Joaquin rivers

The mean annual salinity in San Francisco Bay ranges from 33‰ at the Golden Gate to 0-1‰ in the Sacramento-San Joaquin Delta (Byrne and others 2001). Salinity distribution is determined by the balance between the volume of river inflow and the strength of the tidal cycle. Of the two, the flow of fresh water dominates the environment, accounting for as much as 86% of the observed variability (Peterson and others 1989).

Both the volume and timing of fresh water flow affects the overall variations in annual salinity. The volume and timing of fresh water flow is largely determined by winter precipitation. During December, January, and February, about 55% of the annual precipitation falls. If winter precipitation values are high, then increased runoff from the Sierra Nevada will continue into the summer and the salinity in the estuary will be lower. If winter precipitation is low, then runoff tends to be low in the late spring and summer, and salinity will be high. The volume of runoff generated from winter precipitation is moderated to some extent by spring weather conditions. A wet, cloudy spring leads to a Sierra Nevada snowpack that persists into the summer. Peak river flow will be delayed until late spring or summer. If the spring is warm, peak runoff occurs earlier in the year, leaving little moisture available to moderate summer salinity.

Coastal oceanographic conditions also modify the estuarine response to spring runoff. Because variations in freshwater flow through the estuary far outweigh the marine effect, the role of seasonal upwelling is difficult to separate from the runoff effect.

The Role of the Atmosphere

California's climate is largely controlled by the interaction between the Pacific High and the Aleutian Low pressure systems. During the summer, the Pacific high strengthens over the northeast Pacific, driving storms to the north, into Washington and coastal Canada. In the winter, the high-pressure system weakens and moves southward, allowing the stronger Aleutian low to dominate the weather system. As the gradient between the two pressure systems increases, more storm systems develop and travel a more southerly track into California.

The El Niño-Southern Oscillation (ENSO) events are part of the central California weather system (Schonher and Nicholson 1989). A regional index that incorporates the effect of ENSO events on California weather in general, along with the timing and magnitude of streamflow, has been developed in an attempt to demonstrate the role of regional atmospheric pressure systems on local precipitation (Cayan and Peterson 1989; Dettinger and Cayan 1995).

These ENSO events generally result in increased precipitation in central California. In southern California, the intensity of an ENSO event is connected to the Southern Oscillation Index, but further north, the connection is somewhat tenuous. The Aleutian low is usually stronger during an ENSO event, and if it forms farther east than usual, high-volume precipitation falls in central California during the winter.

The Pacific Decadal Oscillation (PDO) is an ENSO-type pattern that exists across the Pacific basin. The PDO differs from the ENSO in both the length of each oscillation (20-30 years vs. 6-18 months) and region affected (North Pacific/North America vs. the tropics). The PDO appears to be linked to longer-term variability in precipitation and streamflow in the western U.S. (Cayan and others 1993,

1998; Dettinger and others 1998; Nigam and others 1999). The record of these atmospheric-precipitation connections exists for a period of about a century.

The Role of Biology

Both the amount of freshwater and the timing of its distribution affects the diatom floras in the marshes on northern San Francisco Bay. Lehman (1992, 1997, 2000a, 2000b) and Lehman and Smith (1991) noted substantial variations in the algal floras in the upper part of the San Francisco Bay estuary between wet and dry years. Because salinity is not the only variable that affects the composition of a diatom assemblage, the observed lack of consistency between several wet and dry intervals may be related to the timing of maximum freshwater flow and substantial variations in nutrient load between years of high and low freshwater flow (Peterson and others 1989).

Spring or summer runoff is the principle controlling factor in the nutrient budget in the northern part of San Francisco Bay. The combination of nutrient (nitrogen, phosphorous, silica) levels and insolation control both the diversity and taxonomic composition of the diatom flora at any given time.

The Late Holocene Record

Only a handful of studies have addressed the pre-1850 history of freshwater flow through the Sacramento-San Joaquin Delta and its significance in unraveling the complex history of late Holocene climate history in central California (Byrne and others 2001; Goman and Wells 2000; Ingram and DePaolo 1993; Ingram and others 1996a, 1996b; May 1999; Wells and Goman 1995). The purpose of this paper is to demonstrate the effectiveness of diatoms as indicators of centennial-scale climate change.

Methods

The brackish marsh at Rush Ranch (Solano County) was chosen because it lies midway between the normal marine environment of north San Francisco Bay and the freshwater environment of the Sacramento-San Joaquin Delta (Byrne and others 2001). Decadal to centennial-scale fluctuations in freshwater flow are difficult to identify in marshes in northern San Francisco Bay (Starratt, unpublished data) and further east in the Sacramento-San Joaquin Delta (Goman and Wells, 2000; May, 1999; Starratt, unpublished data; Wells and Goman, 1995) due to the lower variability at sites that lie at the marine and freshwater ends of the salinity spectrum. The Rush Ranch site is a small, unreclaimed relict of the tidal marshes that bordered Suisun Bay 150 years ago. During the 20th century the area was grazed by cattle and the hydrology was significantly influenced by water diversion (Nichols and others 1986).

The core (four sections, 3.5 m in total length) was collected using a modified Livingstone corer. The diatom assemblages from a total of 70 samples were tabulated. Samples were prepared using standard acid techniques and mounted using Naphrax. The counting method of Schrader and Gersonde (1978) was followed and, where possible, at least 300 individual frustules were counted.

Despite the available taxonomic literature, the diatom floras of the western U.S. freshwater and estuarine environments are poorly known. Many of the taxa are generally combined into groups of species, without detailed taxonomic differentiation. This method sometimes results in limited ecological and chronological resolution. It is also probable that some of the taxa are new to science.

The assignment of environmental preferences for particular taxa is tenuous at best. There is little agreement within the literature as to what physical and chemical parameters should be measured, as well as how those data should be presented. No such data set currently exists for the San Francisco Bay area. The ecological limits of some taxa (particularly the marine forms) is well established, while information on the brackish and freshwater taxa is more variable. The ecological preferences used in this paper are based on physical and chemical data taken from several recent lake and estuarine studies (Cumming and others 1995; Dixit and Smol 1994; Snoeijs 1993; Snoeijs and Balashova 1998; Snoeijs and Kasperoviien 1996; Snoeijs and Potapova 1995; Snoeijs and Vilbaste 1994; Whitmore 1989).

Results

A detailed discussion of the chronology and stratigraphy of the Rush Ranch core can be found in Byrne and others (2001). A total of four AMS radiocarbon dates were obtained from seeds and rhizome material (Figure 2). The age of sediments at the base of the core is approximately 3,000 cal yr B.P. The sediment accretion rate ranges from 0.6 to 1.6 mm/yr. These values are generally consistent with data from other sites (Byrne and others 2001) in the northern part of San Francisco Bay which indicate that marshes in the region began to expand between 2,000 and 3,000 years ago.

To make a generalized interpretation of salinity variations downcore, most of the taxa were assigned to salinity categories (Figure 2):

- Freshwater: Taxa whose optimum population falls within the salinity range of $< 2\text{‰}$
- Freshwater and brackish water: Taxa whose optimum population falls within the salinity 0‰ to 30‰
- Brackish: Taxa whose optimum population falls within the salinity range of 2‰ to 30‰
- Brackish and normal marine: Taxa whose optimum population falls within the salinity range of 2‰ to $> 30\text{‰}$
- Normal marine: Taxa whose optimum population falls within the salinity range of $> 30\text{‰}$
- No salinity preference: Cosmopolitan taxa that demonstrate no salinity preference

Using these salinity categories, five intervals were identified: lower brackish, lower freshwater, upper brackish, upper freshwater, and post-1850 (Figure 2). The lower freshwater interval is characterized by a more diverse flora than the upper freshwater interval, which is dominated by only a few species (Figure 3). Both the brackish intervals contain a diverse flora.

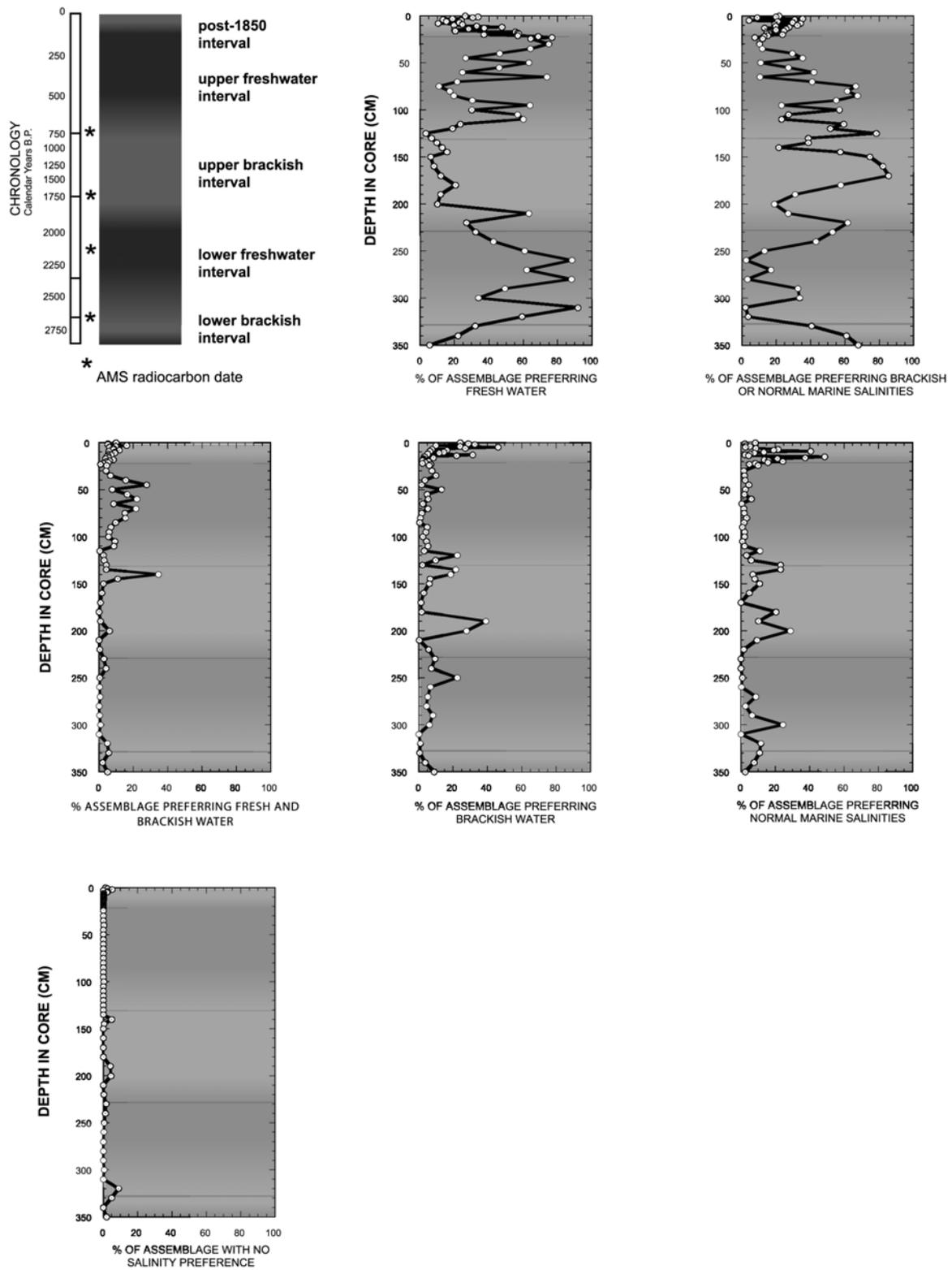


Figure 2 Five intervals representing variations in salinity at Rush Ranch. Diatom salinity preferences shown as percentage of total diatom assemblage. Chronology in calendar years B.P.

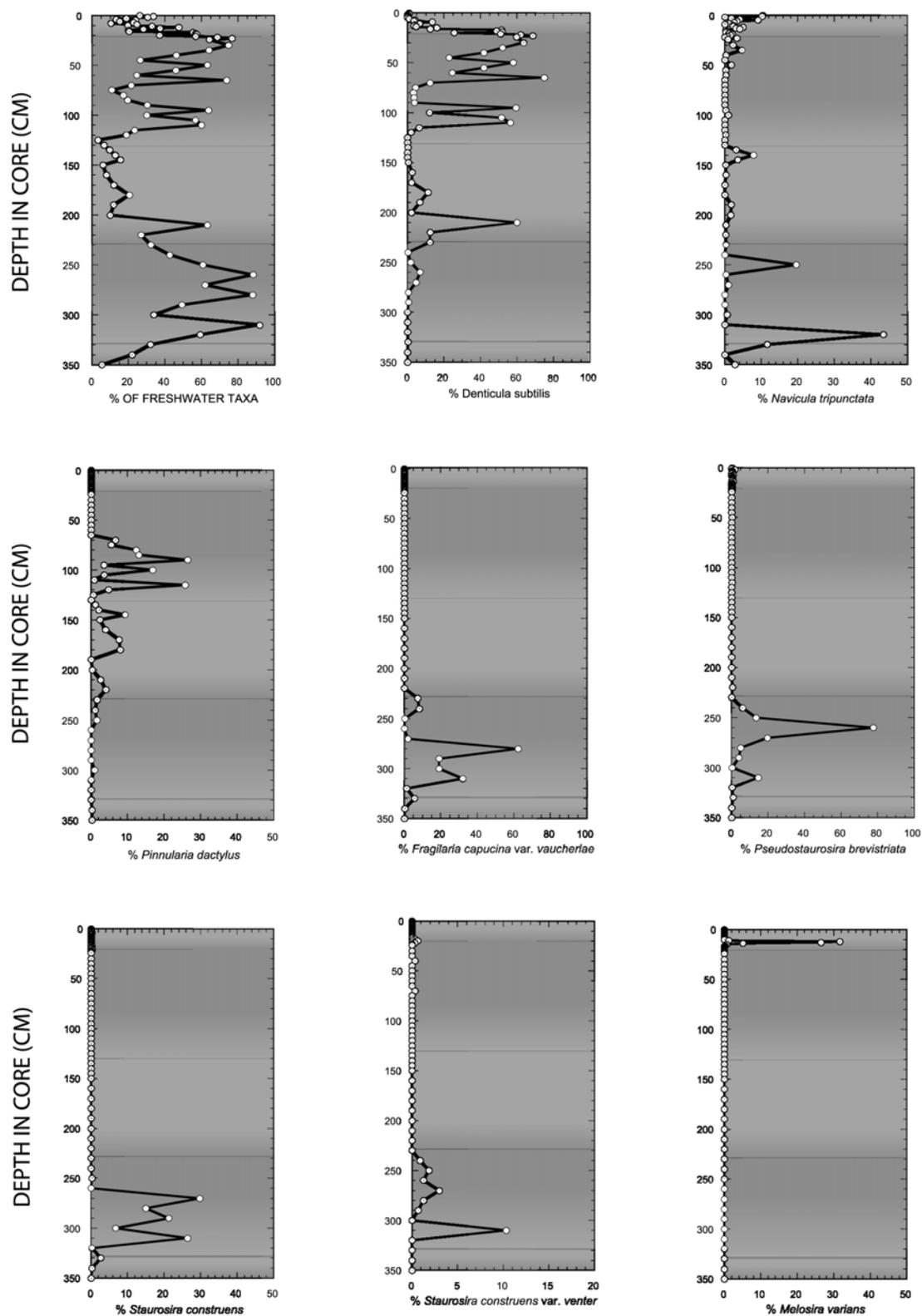


Figure 3 Freshwater assemblage abundance as a percentage of the total assemblage. Dominant taxa in the lower and upper freshwater intervals as a percentage of total flora. Percentage scale is variable.

Freshwater Taxa

A total of 74 taxa with a preference for freshwater have been identified in the samples. Of those taxa, 56 are associated with a benthic habitat, six in a planktonic habitat, and 12 are found in both habitats. In most samples, benthic taxa are the numerically dominant group. Taxonomic distribution within the assemblage is not equitable, with only 10 taxa constituting more than 10% of any one assemblage. In most cases, only one or two taxa dominate the assemblage. The remainder of the assemblage may include 25 to 30 taxa, many accounting for less than 1% of the flora. The majority of the taxa prefer a slightly alkaline environment.

Denticula subtilis is the dominant taxon in the upper freshwater interval, comprising more than 70% of the assemblage in several samples. In one sample in the lower freshwater interval, *D. subtilis* comprises more than 60% of the assemblage. This species is not present in any of the more brackish intervals. Members of this genus are commonly found in oligotrophic (low nutrient load) environments. *Pinnularia dactylus* is co-dominant with *D. subtilis* in the lower part of the upper freshwater interval; it is also the dominant freshwater taxon in the upper brackish interval. *Tryblionella gracilis* was the dominant benthic taxon at the time of European contact; over the past 150 years this dominance has been greatly reduced with increasing brackish water influence caused by increased diversion of water for agriculture. *Navicula tripunctata* and *Amphora ovalis* occur sporadically throughout the length of the core, but are significant in the lower part of the lower freshwater interval. Both these taxa are epilithic (attached to hard substrates), and are found in mesotrophic (moderate nutrient load) to eutrophic (high nutrient load) environments. Several other taxa, which occur in much smaller numbers, are also found in mesotrophic and eutrophic environments.

In the lower freshwater interval, the dominant taxa are obligate planktonic forms (*Fragilaria capucina* var. *vaucheriae*, *Pseudostaurosira brevistriata*, *Staurosira construens*, *Staurosira construens* var. *venter*). In single samples, these taxa comprise as much as 80% of the assemblage. *Melosira varians* briefly dominates the assemblage at the top of the upper freshwater interval. All of these taxa favor eutrophic environments. True planktonic freshwater taxa comprise only a few percent of the total assemblage in any sample.

Freshwater and Brackish Taxa

Taxa (7 benthonic; 2 planktonic) that favor both freshwater and brackish environments are a significant part of the assemblage only in the upper freshwater interval. *Tryblionella acuminata* accounts for more than 30% of the assemblage in the 140 cm sample, but only occurs sporadically elsewhere in the core, particularly below 140 cm. *Epithemia turgida* is a significant component of the flora in the upper freshwater interval, comprising between 10 and 15% of the assemblage in several samples between 40 and 100 cm. Planktonic taxa favoring both freshwater and brackish environments comprise as much as 15% of the assemblage in the upper freshwater interval. These taxa (*Cyclotella striata* and *C. menegheniana*) are also present in the post-1850 interval.

Brackish Taxa

Taxa characteristic of brackish water are distributed throughout the length of the core. The members of this group are most common at the top of the lower freshwater interval and in the post-1850 interval, where they comprise as much as 40% of the assemblage. *Rhopalodia gibberula* is present throughout the core and is a dominant member of the assemblage in samples from both the freshwater and brackish intervals. Short-term increases in the dominance of *R. gibberula* occur in the lower freshwater interval, upper brackish interval, and the post-1850 interval. This taxon also occurs in smaller numbers throughout the upper freshwater interval. *Achnanthes brevipes* var. *intermedia* occurs in small numbers throughout the length of the core, with one dominance peak at the top of the upper brackish interval. *Nitzschia obtusa* var. *scalpeliformis* and *N. sigma* are a significant part of the assemblage in the upper brackish and post-1850 intervals.

Brackish and Normal Marine Taxa

The overall abundance of the portion of the assemblage assigned to a brackish and marine salinity preference is due to varying abundances of *Navicula peregrina* and *Diploneis smithii*. *Navicula peregrina* reaches its greatest abundance (almost 80%) in the lower and upper brackish intervals. It is also a significant component of both freshwater intervals. The abundance of *N. peregrina* varies widely (0% to 30%) within a few centimeters of the core. *Diploneis smithii* is most abundant in the upper freshwater interval, where it comprises as much as 40% of the assemblage. Within this interval, the abundance of *D. smithii* varies from 0% to greater than 40% in the middle of the upper freshwater interval. In the upper part of the upper freshwater interval and the post-1850 interval, *D. smithii* is the dominant brackish and marine taxon, where as it is only a minor component of the lower brackish and lower freshwater intervals. The distribution of *Caloneis westii* somewhat mimics that of *N. peregrina*. *Paralia sulcata* (both large and small forms) do not comprise a significant part of the assemblage in any sample. This taxon is most common (up to 4%) in the upper part of the upper freshwater and post-1850 intervals.

Normal Marine Taxa

Marine taxa comprise a significant part of the assemblage in only a few samples. *Tryblionella granulata* and *T. granulata* var. 1 (Laws 1988) dominate the assemblage in the lower part of the post-1850 interval. Other abundance peaks occur in the lower and upper brackish intervals, as well as the lower part of the lower freshwater interval. Normal marine planktonic taxa never comprise more than 2% of the total assemblage.

Taxa Showing No Salinity Preference

Four taxa show no salinity preference. All occur in small numbers, generally within the brackish intervals and the post-1850 interval. In addition, 24 taxa have not been assigned to an environment based on salinity preference. In any one sample, these taxa rarely account for more than 1% of the assemblage.

Discussion

The downcore distribution of the diatom flora can be broadly separated into three intervals dominated by taxa that favor brackish and marine salinities, and two intervals dominated by freshwater taxa (Figure 2). These intervals correspond to intervals delineated using pollen and ^{13}C data (Byrne and others 2001). In addition to serving as an indicator of the salinity of the waters of the Sacramento River, and thereby, as a proxy for precipitation, diatoms also provide information on the trophic structure and pH of the river water.

Data on pH and trophic (nutrient) levels of individual taxa are generally limited to freshwater taxa (Stoermer and Smol 1999). Indicators of high nutrient levels in coastal marine environments (e.g. *Chaetoceros* spp.) are absent. The taxa present in the lower and upper freshwater intervals prefer a neutral to slightly alkaline environment. The exception is the acidophilic (preferring a slightly acidic environment) species *Eunotia monodon*, which comprises up to 1% of the assemblage in the upper freshwater interval. The freshwater taxa in the lower freshwater interval are dominated by the mesotrophic to hypereutrophic (very high nutrient load) taxa *Amphora ovalis*, *Fragilaria capucina* var. *vaucheriae*, *F. crotonensis*, *Navicula tripunctata*, *Nitzschia palea*, *Pseudostaurosira brevistriata*, *Staurosira construens*, and *S. construens* var. *venter*. The majority of these taxa are obligate planktonic taxa which begin their lives in the littoral zone and later form planktonic mats. The upper freshwater interval is dominated by marginally mesotrophic *Denticula subtilis*. The taxa in the post-1850 interval are a mix of oligotrophic to eutrophic taxa. The difference in the floras in the lower and upper freshwater intervals (Figure 3) may reflect variations in the rate of water exchange at Rush Ranch, with the more eutrophic taxa representing stagnant conditions. However, there is little information on diatom preferences for stagnant or flowing water. The few taxa common in the brackish intervals suggest that the water was slightly alkaline, whereas they provide little or no information on trophic structure.

The majority of the benthonic taxa are either epilithic or epipellic (attached to sediment), with a few epiphytic (attached to plants) species. Until studies of living distributions in San Francisco Bay are conducted, it will be difficult to determine whether the distribution patterns represent autochthonous or allochthonous taxa.

Comparison with other Long-Term Climate Records

The timing of the salinity variations at Rush Ranch can be placed both in the context of global climatic events and anthropogenic intervention within the Sacramento-San Joaquin watershed. The upper part of the upper brackish interval (A.D. 600-1250) corresponds with the Medieval Warm Period and the upper part of the upper freshwater interval (A.D. 1550-1850) corresponds to the Little Ice Age. The increase in salinity at the top of the core may be related to local human impact rather than global climate variations.

Ingram and DePaolo (1993) and Ingram and others (1996a, 1996b) developed a paleosalinity record for San Francisco Bay using strontium isotopes. Using paleosalinity values, a discharge record for the Sacramento-San Joaquin Delta was calculated for the past 700 years. This record broadly correlates with the variations in the abundance of freshwater taxa at Rush Ranch. Most noticeable in the discharge record is an abrupt increase in discharge corresponding to the onset of the Little Ice Age

(middle 16th century) and an abrupt decrease in discharge in the late 1800s, corresponding with increased agriculture in the Sacramento and San Joaquin valleys. Similar abrupt changes occur in the Rush Ranch diatom record.

Tree-ring records from the southern and central Sierra Nevada, White Mountains, and northern Sacramento Valley reflect similar patterns in precipitation as those observed at Rush Ranch. Scuderi (1987a) obtained a 4,000 year record from Cirque Peak in the southern Sierra Nevada and two sites in the neighboring White Mountains. Major decreases in timberline elevation centered at 2,400 and 400 years ago correspond with intervals that contain a high percentage of freshwater taxa (70% to 90%). A less significant downslope change in timberline centered at 600 years ago corresponds to an interval of increased freshwater influence within the upper brackish interval. Increases in the elevation of the treeline in the White Mountains during intervals centering on 900 and 600 years ago correspond with relatively low occurrences of freshwater taxa at Rush Ranch. More detailed records covering the last 1,200 years (Scuderi 1987b) demonstrate a correspondence between decreasing temperature and increasing abundance of freshwater taxa at Rush Ranch. Periods of decreased temperature derived from southern Sierra Nevada tree-ring records (Scuderi 1993) correspond to an increase in the abundance of freshwater taxa at Rush Ranch.

Hughes and Brown (1992) and Hughes and others (1990) utilized giant sequoias [*Sequoiadendron giganteum* (Lindl.) Bucholtz] at low elevation sites to calibrate the tree-ring record with the Palmer Drought Severity Index. This tree-ring analysis indicated that short intervals (2 to 4 years) of low growth were common throughout the 2089-year record (1127 BC to AD 1989). Periods of substantially longer drought corresponded to intervals of decreased freshwater flow at Rush Ranch. Several intervals of extended drought occurred during the upper brackish interval. These intervals may be related to slight variations in the abundance of freshwater taxa at Rush Ranch. However, these slight variations may also suggest that the dominant control on water volume flowing through the Sacramento-San Joaquin Delta at the time was the input from the northern part of the watershed. The longest period of extended drought corresponds with the increase in freshwater flow that occurs before the Little Ice Age.

Earle (1993) developed precipitation records from northern and central California and a discharge record for the Sacramento River based on tree-ring analysis. Positive and negative precipitation anomalies in northern California more closely correspond to river discharge variations which, in turn, correspond closely with variations in the abundance of freshwater diatoms at Rush Ranch. The reconstructed precipitation record for central California shows similar variations, although some of the shorter fluctuations are absent. In some cases the magnitude of the anomalies in central California precipitation is less than that in northern California, suggesting that the predominant source of moisture at this time was the upper Sacramento basin. Graumlich (1987) extended the tree-ring record from California to Washington. In her southern valley region, which includes several sites in northern California, the most notable correlation with the Rush Ranch record is a large positive precipitation anomaly during the later half of the 19th century, which corresponds to an increase in freshwater taxa and the large negative anomaly between 1910 and 1935, which corresponds with a low abundance of freshwater taxa. It should be noted, however, that this correspondence may be tainted by human manipulation of the Sacramento River watershed.

Benson and others (1999; personal communication 2001) demonstrated a strong correlation between fluctuations in historic lake levels in northern Nevada and surface-water supply to the Sacramento-San Joaquin Delta. Applying these correlations to a 2,700-year long ¹⁸O record from Pyramid Lake, Nevada, they described 18 cycles of lake level variation. A similar pattern in freshwater flow variation may be reflected in the data from Rush Ranch.

The lake level record from Mono Lake (Stine 1990) provides a 1,800-year chronicle of precipitation in the west-central Great Basin. During that time, six or seven high lake level stands were identified (Figure 4). High and low stands correlate, respectively, with some of the high and low abundances of freshwater taxa at Rush Ranch. The Marina Low Stand and Lee-Vining Delta Low Stands correlate well with the beginning and end of the upper brackish interval, and the Mill Creek-East High Stand correlate well with the later of the two intervals with a higher abundance of freshwater taxa. The Marina Low and Lee-Vining Delta Low stands correspond to the intervals of lowest freshwater diatom abundance in the Rush Ranch record. During the past 1,000 years, the five high stands at Mono Lake are higher than those that occurred during the previous 800 years; during the same interval the abundance of freshwater diatoms is greater than during the previous 1,200 years. The low stands are not as low as either the Marina Low or Lee-Vining Delta Low stands. The Historic High and Historic Low stands are difficult to identify due to the effect of post contact alteration of the drainage.

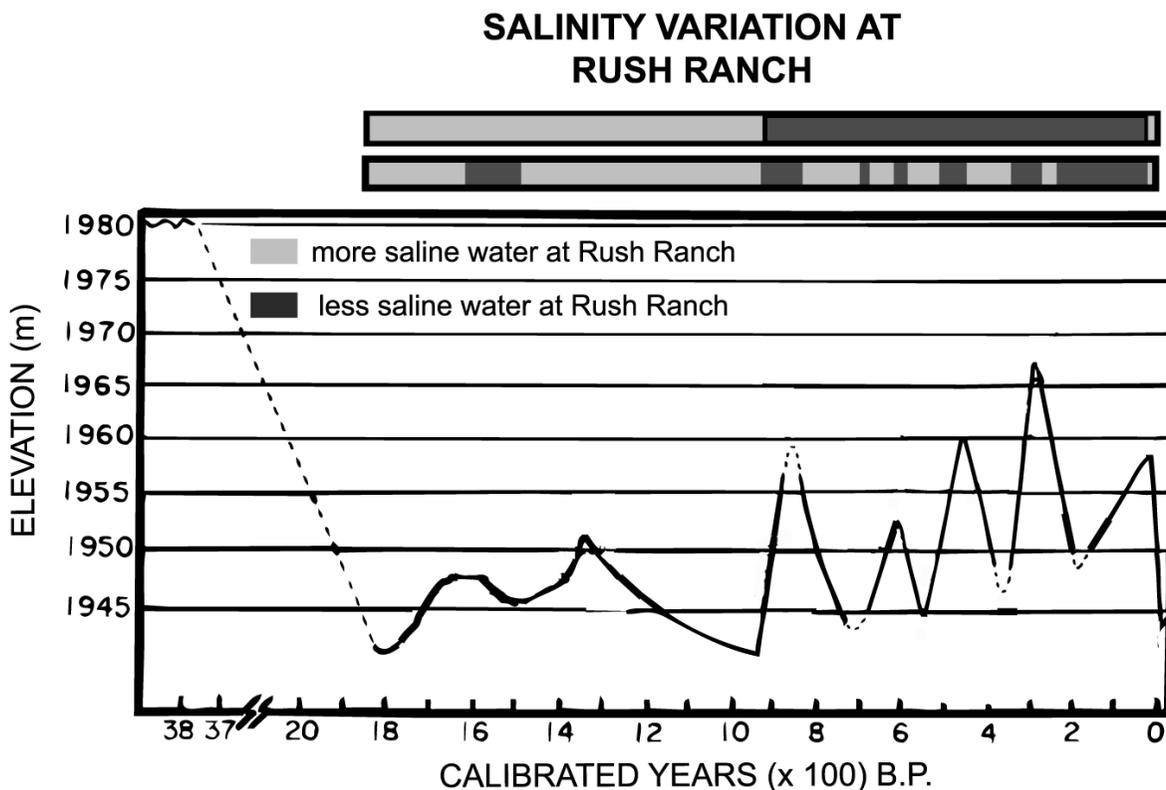


Figure 4 Variation in lake level at Mono Lake, California (modified from Stine 1990) compared with variation in fresh water diatom abundance at Rush Ranch

Conclusion

The diversity of the diatom flora at Rush Ranch is higher than previously reported for San Francisco Bay. There are two reasons for this: (1) previous studies were limited to marine and marginal marine environments which limited the number of taxa present and (2) one of the purposes of this study is to expand the knowledge of diatom diversity in San Francisco Bay. While it has been possible to increase the list of taxa found in San Francisco Bay, and most taxa can be assigned to a salinity preference based on the literature, the ecological significance of these taxa is not entirely clear. Detailed field information on present-day environmental preferences of these taxa, as well as determining what portion of the flora at each site is transported, will increase the value of environmental and climatic interpretations, enabling one to elucidate a possible climate record.

Comparison of the salinity-based discharge record for the Sacramento-San Joaquin river system indicates that diatoms are useful proxies for climate change in estuarine systems. High abundances of freshwater diatoms at Rush Ranch correspond to high lake levels at Mono Lake, and may also correspond to high lake levels at both Lake Tahoe and Pyramid Lake. There is also a strong correspondence between the tree-ring precipitation record and the discharge record. Discrepancies between the northern, southern, and coastal tree-ring records indicate that for the past 3,000 years most of the water flowing through the Sacramento-San Joaquin Delta originated in the Sacramento Basin.

At this stage, only a preliminary connection can be made between the fossils and regional-scale atmospheric processes. The two brackish intervals may represent intervals when the Aleutian low migrated further south and east, creating a wetter winter and spring. The opposite may be true during the more normal marine intervals when a stronger and more northerly Pacific high may have created relatively dry winter conditions.

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